Fabrication of narrow pulse passively Q-switched self-stimulated Raman laser with c-cut Nd:GdVO4*

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Combining the self-stimulated Raman scattering technology and saturable absorber of Cr^{4+}:YAG, a 1.17 μm c-cut Nd:$GdVO_4$ picosecond Q-switched laser is demonstrated in this paper. With an incident pump power of 10 W, the Q-switched laser with average power of 430 mW for 1.17 μm, pulse width of 270 ps, repetition rate of 13 kHz and the first order Stokes conversion efficiency of 4.3% is obtained. The Q-switched pulse width can be the narrowest in our research. In addition, the yellow laser at 0.58 μm is also achieved by using the LiB_3O_5 frequency doubling crystal.

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The Q-switched and continuous wave (CW) self-Raman lasers based on Nd-doped and Yb-doped crystals have been demonstrated, which provide the first Stokes line in the near infrared region between 1 100 nm and 1 200 nm[1-6]. When stimulated Raman scattering (SRS) is combined with the second-harmonic generation or sum frequency generation, these lasers can generate radiation at wavelengths ranging from yellow to orange spectral region. These systems are compact and versatile, and by choosing different crystals, a range of output wavelengths can be obtained for potential applications in many fields, such as medicine, biomedicine, remote sensing and so on. The CW yellow-orange laser can be achieved by sum frequency. However, the yellow-orange pulse laser is difficult to achieve, which can be a potential light source in many fields, such as ecological monitoring and medical applications.

Nd:$GdVO_4$ crystal is predicted to be a promising material suitable for SRS. With the Nd:$GdVO_4$ crystal, many Q-switched self-Raman lasers have been demonstrated experimentally[7-10]. Many groups have studied the c-cut Nd-doped vanadate crystal Q-switched Raman laser[5-7,11]. Furthermore, SRS can be used in pulse compression technology[12].

In order to achieve narrower pulse width of Q-switched self-Raman laser, in this paper a c-cut Nd:$GdVO_4$ and a Cr^{4+}:YAG are used, and the design of the cavity is considered seriously. And an LBO crystal is chosen as the frequency doubling crystal for the high damage threshold, large acceptance angle, and large nonlinear coefficient. A 10-mm-long LBO crystal was cut for type-I critical phase matching (θ=90°, φ=3.7°). The LBO is placed in the external cavity and no focal lens is used. A compact and effective laser system is demonstrated in our experiment. Compared with other groups[5-9,13-15], we have realized the narrowest Q-switched pulse width of 270 ps.

The experimental device is shown in Fig.1. The pump source is a fiber-coupled 808 nm laser diode (LD) with a core diameter of 200 μm and a numeric aperture of 0.22. The central wavelength of the laser diode is 807. 5 nm at 25 °C and can be tuned by changing the working temperature of the LD to match the best absorption of the laser crystal. The active medium is a c-cut Nd^{3+}:$GdVO_4$ (3 mm×3 mm×12 mm, 0.2% of atomic percentage). The crystal was high-transmission (HT) coated at 808 nm and 1 063 nm (>99.8%). The laser crystal was wrapped with indium foil and mounted in a water-cooled copper holder. The water temperature was controlled to be 18 °C to ensure stable laser output. The resonator consists of two mirrors, M_1 and output coupler (OC), a c-cut Nd:$GdVO_4$, and a Cr^{4+}:YAG absorber. The mirror M_1 is a spherical mirror with a curvature radius of 100 mm, which was anti-reflection (AR) coated at 808 nm (>98%) and high-reflection (HR) coated at 1 063 nm and 1.17 μm (>99.8%). The OC is a flat mirror which was high-reflection (HR) coated at 808 nm and 1 063 nm and partial-transmission (PT) coated at 1.17 μm (T=5%, 15%, 30%). The total optical-cavity length is about 18 mm. The mirror M_2 is a 45° flat mirror which was high-transmission (HT) coated at 1 063 nm and high-reflection (HR) coated at 1.17 μm, which is used as an optical filter

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to separate fundamental laser with Raman laser.

In this experiment, a Cr^{4+}:YAG with 75% initial transmission at 1 063 nm is used and both sides of the laser crystal were coated with anti-reflection layer for the 1 063 nm radiation. In order to achieve good passively Q-switched laser, the criteria can be given by[16]

$$\ln(1/T_0^2)\cdot\left[\ln\left(1/T_0^2\right)+\ln(1/R)+L\right]^{-1}\times$$
$$\left(\sigma_s/\sigma_g\right)\cdot\left(A_g/A_s\right)>r/(1-\beta)\,, \quad (1)$$

where T_0 is the initial transmission of the saturable absorber, A_g/A_s is the ratio of the effective area in the gain medium to that in the saturable absorber, R is the reflectivity of the output power, L is the non-saturable intracavity roundtrip dissipative optical loss, σ_s is the ground-state absorption cross section of the saturable absorber, σ_g is the stimulated emission cross section of the gain medium, r is the inversion reduction factor with a value between 0 and 2, and β is the radio of the excite-state absorption cross section to that of the ground-state absorption in the saturable absorber. A_g/A_s should be as large as possible for realizing effective Raman scattering easily. From the ABCD matrix, A_g/A_s is proportional to the length of cavity. In other words, the shorter the length of cavity, the smaller the A_g/A_s. Due to this reason, the Cr^{4+}:YAG should be placed as closely as possible to the OC, and the Nd:$GdVO_4$ crystal was placed as closely as possible to the input mirror M_1. The mode radii at the center of the active medium and Cr^{4+}:YAG can be calculated as 290 μm and 80 μm, respectively.

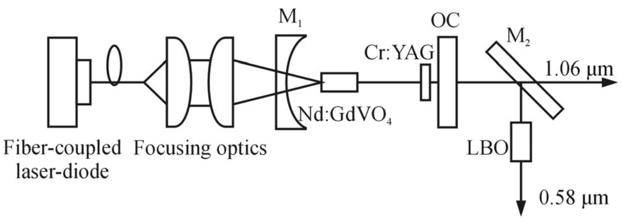

Fig.1 Schematic for the Q-switched mode-locked self-Raman Nd-doped vanadate crystal laser

The mode-locked pulses were detected by a high-speed InGaAs photodetector (10 GHz bandwidth) and a digital oscilloscope (LeCroy Wave pro 7300A) with 3 GHz electrical bandwidth. The spectra of the 0.58 μm yellow lasers were detected by an ocean spectrometer (HR 2000+).

In order to realize better Q-switched self-Raman laser output, different transmission spectra of OC (*T*=5%, 15%, 30%) are compared. Fig.2 shows the output power at 1.17 μm respect to the incident pump power with three kinds of OC. When *T*=5%, the threshold of Raman laser is about 5 W, the slope efficiency is $k_{5\%}$=2.02%, and the maximum average output power is 330 mW. When *T*=15%, the threshold of Raman laser is about 5.5 W, the slope efficiency is $k_{15\%}$=2.84%, and the maximum average output power is 430 mW. When *T*=30%, the threshold of Raman laser is about 6 W, the slope efficiency is $k_{30\%}$=2.06%, and the maximum average output power is 335 mW. Comparing the data above, using the OC with *T*=15%, the operation of laser mechanism has the highest output power and slope efficiency.

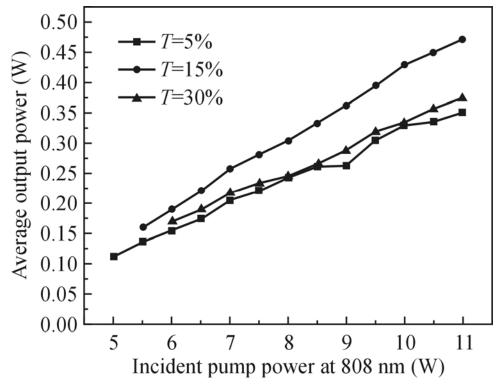

Fig.2 Average output power at 1.17 μm with respect to the incident pump power for *T*=5%, *T*=15% and *T*=30%, respectively

Under the condition of *T*=15%, Fig.3 shows that the Q-switched laser pulse width decreases, while the Q-switched laser repetition rate increases respect to the incident pump power. As to the 1.17 μm Raman laser, the repetition rate changes from 1 kHz to 13 kHz and the pulse width changes from 342 ps to 270 ps, as the incident pump power increases from 6 W to 10 W. At the incident pump power of 10 W, the repetition rate is 13 kHz, and the Q-switched pulse width is only 270 ps. Through calculation, the single pulse energy changes from 0.033 mJ to 0.190 mJ, and the peak power changes from 122.5 kW to 546.0 kW, which are shown in Fig.4.

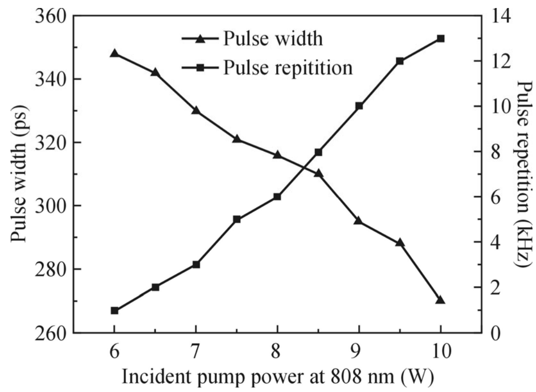

Fig.3 Pulse repetition rate and pulse width at 1.17 μm with respect to the incident pump power for *T*=15%

With an optical filter (1063HT, 1173HR), the pulse train traces are shown on the oscilloscope. At the incident pump power of 10 W, Fig.5(a) shows the pulse of fundamental laser (1 063 nm) on time scale of 2 ns/div, and the pulse of Raman laser (1.17 μm) on the same time scale is shown in Fig.5(b). The laser amplitude fluctuations are relatively small and stable. A comparison between the two figures reveals that the pulse width of the Raman laser is less than that of the fundamental laser.

The LBO is chosen as the frequency doubling crystal, both sides of which are coated with antireflection layers at 1 063 nm and 0.53 μm, respectively. About 8.68 mW yellow-laser output is achieved at 10 W of pump power. The spectrum of the yellow laser is shown in Fig.6.

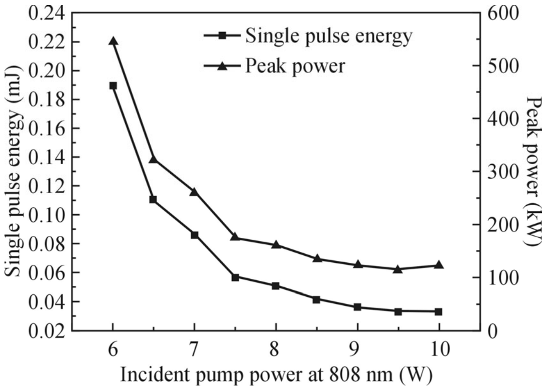

Fig.4 Pulse energy and peak power at 1.17 μm with respect to the incident pump power for *T*=15%

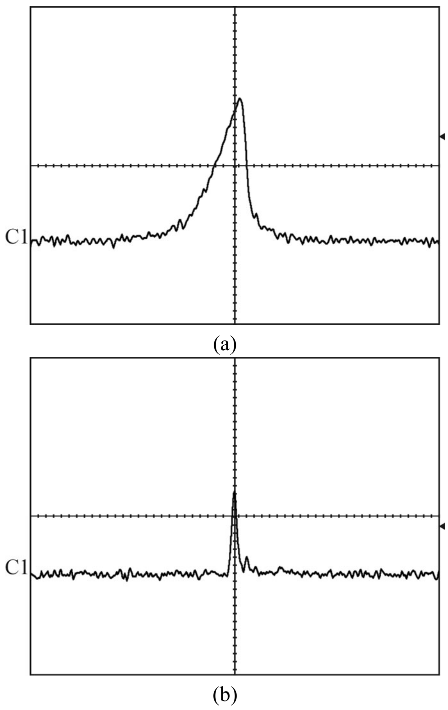

Fig.5 (a) The pulse of fundamental laser at 1 063 nm on scale of 2 ns/div; (b) The pulse of Raman laser at 1.17 μm on scale of 2 ns/div

In conclusion, we have demonstrated a compact passively Q-switched picosecond self-Raman laser with c-cut $Nd:GdVO_4$ crystal. A Cr^{4+}:YAG with 75% initial transmission is used as the Q-switched saturable absorber. As far as we know, the narrowest pulse width of Q-switched laser can be achieved. The repetition rate changes from 1 kHz to 13 kHz and the pulse width

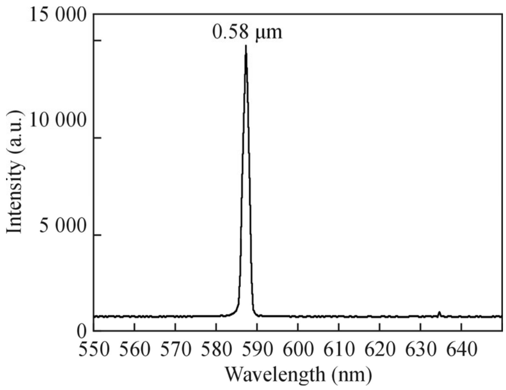

Fig.6 Spectrum of the yellow laser

changes from 342 ps to 270 ps, as the incident pump power increases from 6 W to 10 W. At the incident pump power of 10 W, the pulse width, the maximum average output power and the pulse repetition rate are 270 ps, 430 mW and 13 kHz, respectively. We have obtained 8.96 mW yellow laser output at 0.58 μm, using a 10-mm-long LBO as the frequency doubling crystal.

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